FATIGUE BEHAVIOUR OF ALUMINIUM 6061 IN TAILOR WELDED BLANK

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ABSTRACT

Aluminium is widely used in many welding applications. 6061 aluminium alloy is one of the most common aluminium alloys in automotive industry. Welding is the permanent joining of two materials. The drive towards weight reduction in the automotive industry has led to the use of tailor- welded blanks (TWB) for structural applications. Forming of TWB is one of the challenging welding skills due to a significant reduction of formability associated with the type of blank. The different thickness combinations and compositions will give the different results to tensile test. The local approaches to fatigue have gaining added interest in the analysis of welded joints especially in TWB. In this sense, this research seeks to understand the significance of the fatigue crack initiation evaluated using a local strain-life approach, on the total fatigue life estimation for TIG welding.

ABSTRAK

Aluminium digunakan secara meluas dalam banyak aplikasi kimpalan. Aluminium aloi 6061 adalah salah satu daripada aloi aluminium yang paling biasa dalam industri automotif. Kimpalan adalah proses menggabungkan dua bahan. Usaha ke arah pengurangan berat produk dalam industri automotif telah membawa kepada penggunaan khusus kimpalan kosong (Twb) untuk aplikasi struktur. Membentuk kimpalan kosong (Twb) adalah salah satu kemahiran kimpalan yang mencabar disebabkan oleh pengurangan ketara kebolehbentukan dikaitkan dengan jenis kosong. Kombinasi ketebalan yang berbeza dan komposisi akan memberikan hasil yang berbeza untuk ujian tegangan. Pendekatan tempatan untuk keletihan bahan telah mendapat kepentingan dalam analisis dkimpalan terutama dalam Twb. Oleh itu, kajian ini bertujuan untuk memahami kepentingan permulaan retak keletihan, dinilai menggunakan pendekatan tekanan hidup tempatan, kepada jumlah anggaran hayat maksima untuk kimpalan TIG.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ASTM	American Society for Testing Materials
AISI	American Iron Steel Institute
EDM	Electric Discharge Machining
RPM	Revolution Per Minute
TIG	Tungsten Inert Gas
SEM	Scanning Electron Microscope

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Aluminium is widely used in many welding applications. 6061 aluminium alloy is one of the most common aluminium alloys for heavy duty structures requiring good corrosion resistance and widely used in automotive industries (Alfredo and Abilio, 2011).Welding is the permanent joining of two materials usually metal through localizes, resulting from a suitable combination of temperature, pressure, thickness ratio and metallurgical conditions (De Garmo, 1974).The various welding process differ considerably in terms of temperature and pressure.

The drive towards weight reduction in the automotives industry has led to the use of tailor- welded blanks (TWB) for structural applications. Forming of TWB is one of the challenging welding skills due to a significant reduction of formability associated with the type of blank. Material property changes in the heat-affected zone of the welded part in terms of decrease the strain in the material prior to tearing failure. The different thickness combinations and compositions will give the different results to tensile test.

Recently, the local approaches to fatigue have gaining added interest in the analysis of welded joints especially in TWB. In general, such approaches are based on a local damage definition which makes these approaches more adequate to model local damage such as the fatigue crack initiation. In this sense, this research seeks to understand the significance of the fatigue crack initiation, evaluated using a local strain-life approach, on the total fatigue life estimation for TIG welding.

1.2 PROBLEM STATEMENT

Forming of TWB is a very challenging due to a significant reduction of formability associated with this type of blank. Properties of materials in Aluminium 6061 alloys changes in the heat-affected zone of the welded part in terms of decrease the strain in the material prior to tensile failure. Thus the failure leads towards the study of fatigue behaviour of the material. The thinner part of TWB maybe undergoes deformation than the thicker part which is stronger material in the forming area. In order to clarify the influence of loading directions, this study continues with different loading direction of welding specimen with angles of 45^o and 90^o to the laser welds line.

1.3 OBJECTIVES

The objectives of this study are:

i. To evaluate the optimum loading direction of welded Aluminium6061 with different thickness.
ii. To determine the joint strength of the welded material through tensile and fatigue test.
iii. To characterize the properties and fatigue fracture of the welded material

1.4 SCOPES OF THE PROJECT

The scopes of this study include:

i. Specimens are specifically Aluminium 6061.
ii. Investigations covered properties of aluminium, ASTM standards, welding requirements process, and microstructure analysis and fatigue behaviour.
iii. Types of welding process used TIG welding.
iv. The preferred angles for loading direction were45^o and 90^o to the welds line.
v. Results elaborated from tensile test, fatigue test and microstructure analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In a simple meaning, fatigue means the temporary lost of strength and energy resulting. Fatigue failure has an appearance similar to brittle fracture, as the fracture surface is flat and perpendicular to the stress axis with absence of necking. This chapter briefly explains about the fracture features of a fatigue failure of welded material. Fatigue test is a method for strain controlled fatigue testing that can determine the low cycle fatigue properties of materials. Different materials have their own properties and for more clear, these chapters reviewed about the properties aluminium 6061 and investigate the joint welded strength using different thickness and different loading direction. TWB is a new technology that widely use all over the world. There are many welding methods in TWB and the strength of each joining will be discussed in this chapter. The intermetallic compound layer is studied to investigate the effect of additions compound in the joining.

2.2 FATIGUE BEHAVIOUR

The fracture features of a fatigue failure, however, are quite different from static brittle fracture arising from three stages of development. Figure 2.1 shows fatigue failure development. Stage1 is the initiation state of one or more micro cracks due to cyclic plastic deformation followed by crystallographic propagation extending from two to five grains about the origin. This stage is not normally discernible to the naked eye. Stage 2 is the progresses from micro cracks to other micro cracks forming parallel plateau-like fracture surfaces separated by longitudinal ridges. The plateaus are generally smooth and normal to the direction of maximum tensile stress. These surfaces can be wavy dark and light bands referred to its beach marks. Stage 3 occurs during final stress cycle when the remaining material cannot support the loads and resulting in a sudden, fast fractures. This stage fracture can be brittle, ductile, or a combination of both. Fatigue crack will typically initiate at a discontinuity in the material where the cyclic stress is a maximum. Discontinuities can arise because of design of rapid changes in cross section, keyways, holes where stress concentration occurs. The elements that roll against each other under high pressure, developing concentrated subsurface contact stresses that can cause surface pitting after many cycles of the load. Composition of the material itself as processed by rolling, forging casting, extrusion, drawing, heat treatment (Budynas and Nisbett, 2011).

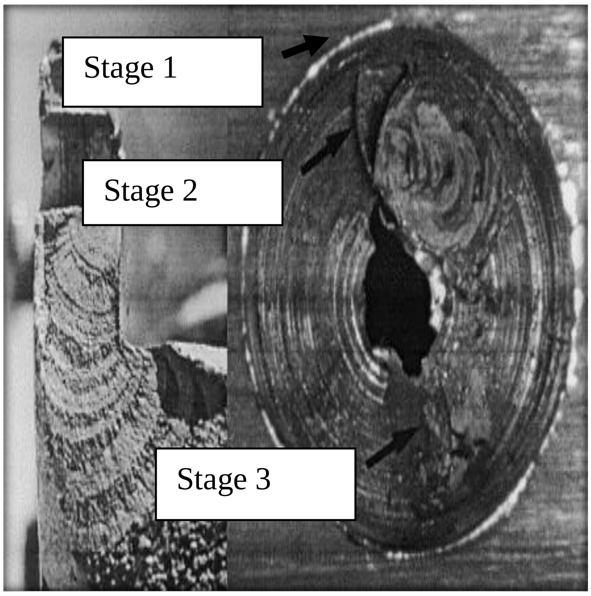

Figure 2.1: Figure of microstructure of fatigue failure of those three stages.

Source: Budynas and Nisbett (2011).

2.3 PROPERTIES OF ALUMINIUM

Aluminium is one of the lightest available commercial metals with a density approximately one third that of steel or copper. Patel et al, (2012) have presented the density of aluminium, steel and copper is 2720, 7850 and 8940 kg/m^3 respectively. Besides it allows the increasing payloads and fuel savings. In other fabrications, aluminium's lightweight can reduce the need for special handling or lifting equipment. Aluminium has excellent resistance to corrosion due to the thin layer of aluminium oxide that forms on the surface of aluminium when it is exposed to air. Table 2.1, Table 2.2 and Table 2.3 summarized the properties of an aluminium alloy.

Table 2.1: Composition of aluminium 6061 prepared by America Standards Metals ASM

Al	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr
95.8 - 98.6	0.8- 1.2	0.4- 0.8	0.7	0.15 - 0.40	0.25	0.15	0.15	0.04 - 0.35

Source: Moreira (2008)

Table 2.2: Strength and elastic properties of the 6061 aluminium alloys.

Properties	6061
Tensile strength, σ_{UTS}(MPa)	290-317
Yield strength, $\sigma_{0.2\%}$ (MPa)	242-279
Elongation, ε_r (%)	10.0-15.8
Young modulus, E (GPa)	68.0

Source: Moreira (2008)

Table 2.3: Strain-life and cyclic properties of the 6061 alloy

Properties	**6061**
Fatigue strength coefficient, f σ (MPa)	394
Fatigue strength exponent, b	-0.045
Fatigue ductility coefficient, ε_f’ (-)	0.634
Fatigue ductility exponent, c	-0.723
Cyclic strain hardening coef., k’ (MPa)	404
Cyclic strain hardening exponent, n′	0.062

Source: Borrego (2004)

2.4 FATIGUE TEST STANDARDS

To avoid poor fatigue properties occurred, clear design guidelines should be followed so that the fatigue failure can be avoided in this welded aluminium alloy structures. Figure 2.2 is the design for ASTM E606 which is test method for strain controlled fatigue testing. This low cycle fatigue testing method covers the determination of low-cycle fatigue properties of nominally homogeneous metallic materials by the use of axially loaded test specimens (ASTM, 1998). It is intended as a guide for low-cycle fatigue testing performed in support of such activities as materials research and development, mechanical design, process and quality control, product performance, and failure analysis.

From a research by Alfredo (2011), he used geometry and dimensions of the specimen in recommendations of ASTM E606 (ASTM, 1998).ASTM E606 is a standard practice for strain controlled fatigue test. The fatigue tests were conducted with constant strain amplitudes, at room temperature, in air.

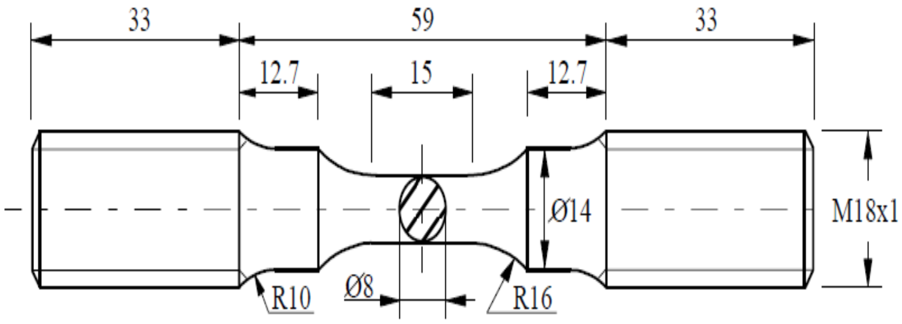

Figure 2.2: Geometry and dimensions of the specimen using ASTM E606 standards

Source: ASTM standards (1998)

The graph as shown in Figure 2.3presents the total strain amplitude versus life curve obtained from the superposition of the elastic and plastic strain amplitude versus life curves. The number of reversals of transition, $2N_T$, verified for 6061-T651 aluminium alloy was 969 reversals**.** One important strain-life relation was proposed by (as cited in Coffin, 1954) and (as cited in Manson, 1954), which relates the plastic strain amplitude, Δεp/2, with the number of reversals to crack initiation, 2Nf.Both ε' and c are respectively, the fatigue ductility coefficient and fatigue ductile exponent.

$$\frac{\boldsymbol{\Delta\varepsilon\, p}}{\mathbf{2}} = \varepsilon' f\,(2Nf)^{c} \quad (2.1)$$

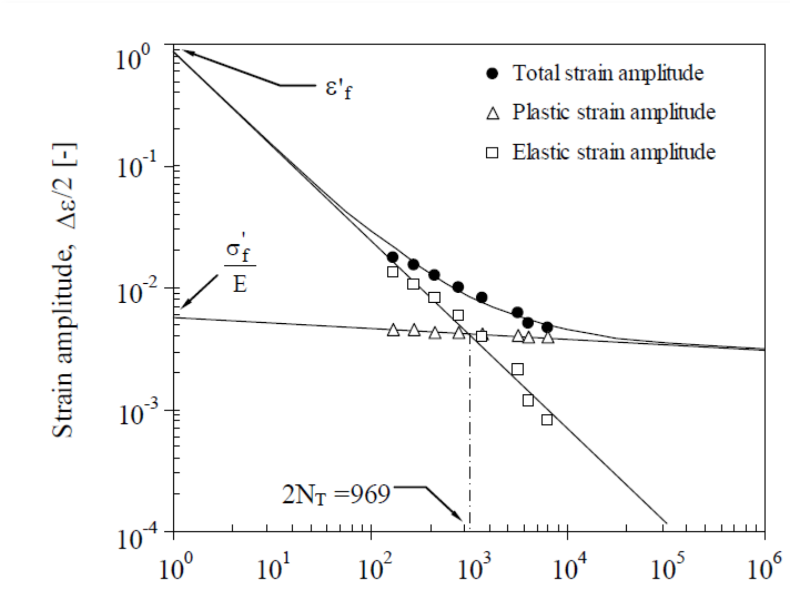

Figure 2.3: Strain life data for 6061-T651 aluminium alloy

Source: Moreira (2008)

2.5 TAILOR WELDED BLANK (TWB)

In the past two decades, the automotive industry has seen constricting government regulations concerning fuel conservation and safety mandates along with the environmental concerns which requires various material options to be welded together prior to the forming process. Such a concept of combining the available material into welded blank, it's enabled engineers to "tailor" the blank so that the best properties of materials were located precisely within the part where they were needed. The differences could be found in the grade, thickness, strength and coating. The TWB are currently used for body side frames, door inner panels, motor compartment trails, centre pillar inner panels and wheelhouse/shock tower panels as shown in Fig 2.4 (Anand et al., 2004). The main advantages for manufactures in using TWB are:

i. The TWB makes it possible to put thick steel only where it is strictly necessary. Weight savings of 20% to 40% are possible according to type of component and the technology employed.
ii. Improve in safety thanks to a better impact resistance and a better dynamic behaviour of the component weight for weight.
iii. Improve in fatigue strength by the replacement of spot weld by continuous weld.
iv. Reduce the number of components and consequently a reduction in production methods and stages, ensuring an increase in productivity while decreasing the investment and cost with regard to stamping and metal forming.
v. Improve vehicle corrosion performance by local optimization of the coating but also through a reduction of the number of reinforcements, thus avoiding box members susceptible to corrosion.

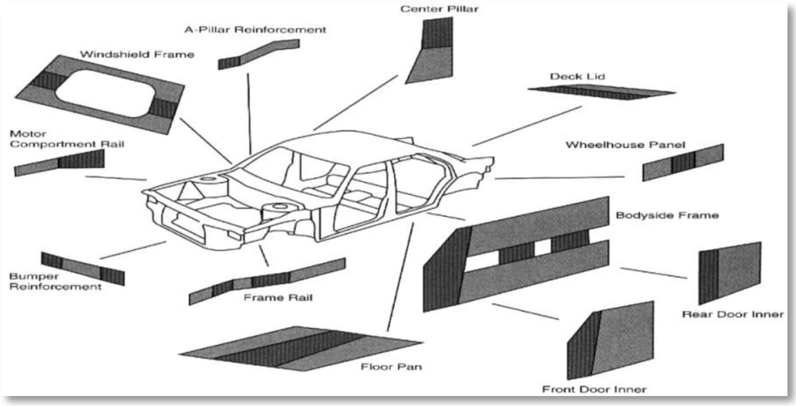

Figure 2.4: Exploded view of current and potential automotive TWB applications

Source: Kinsey and Coa (2003)

2.6 WELDING PROCESS

Welding is joining process that joint two materials together. It can be a permanent joint of two materials usually metal through localizes, resulting from a suitable combination of temperature, pressure and metallurgical conditions. They vary as to the attention that must be given to the cleanliness of the metal surfaces prior to welding and to possible oxidation or contamination of the metal during welding. If high temperature is used, most metal are affected more adversely by surrounding environment (De Garmo, 1974). Figure 2.5 is the examples of weld orientations in TWB.

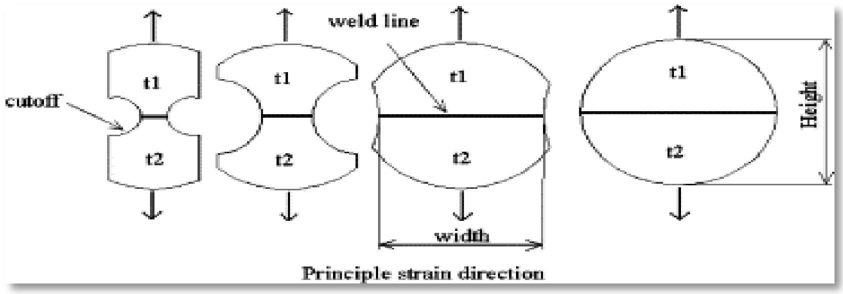

Figure2.5: Weld line orientation of the TWB

Source: Chan (2003)

The weldability of aluminium alloys is unlike carbon steels, not linked as with carbon steel. The problem of transformation phases which coupled with dissolved hydrogen and the mechanical constraints lead to weld brittleness. Their weldability criteria depend like austenitic stainless steel, on the susceptibility to hot cracking or solidification cracking. The compatibility of metals to be welded and the choice of filler metal are also important because they can cause a lack of bead ductility. Effect hydrogen to aluminium alloy is different to steel. With aluminium alloys, it causes gaseous porosities because of the great differences in solubility between the liquid and solid against 0.69 cm^3/100 g at melting point of 660^oc (Regis,2008).

2.6.1 Gas Tungsten Arc Welding (TIG)

Gas tungsten arc welding or also called TIG welding is a process that uses a no consumable tungsten electrode and an inert gas for art shielding. Filler metal is added to the weld pool from a separate rod or wire. The filler metal will be melting by the heat of the arc. Because of the tungsten has high melting point, (341^oc) it is classified as good electrode material. Gas tungsten arc welding applicable to all metal in a wide range stock of thickness and also can be use for joining various combinations of dissimilar material. The most common application for these applications is stainless steel and aluminium (Groover, 2004).

Figure 2.6 shows the TIG welding process. This welding process is perfectly adapted to very thin products, making it possible to obtain high quality welds, with low output. Welding speed is generally about 15-50 mm/sec. The welding parameters for steel welding are determined by the nature and composition of the base metal, the thickness to be assembled and the fastening method. TIG welding can be performing in all position and it is easy to use. Besides that, it has no filler metal is carried across the arc and there is no little and spatter at the material. Figure 2.7 shows a schematic diagram showing the weld bead geometric parameters. The weld is also more smoother since there is no slug produced that might be trapped in the weld (Kalpakjian, 2001).

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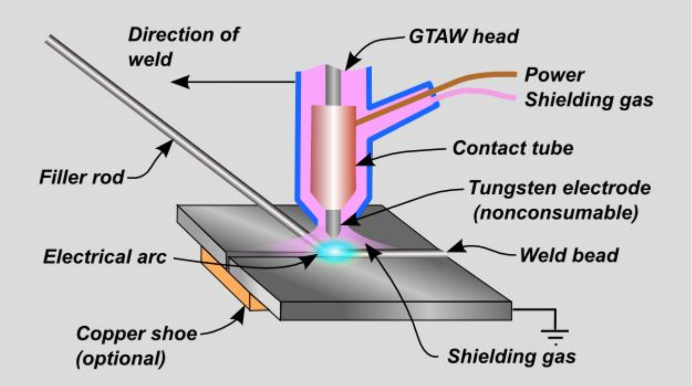

Figure 2.6: The TIG welding process

Source: Kalpakjian, (2001)

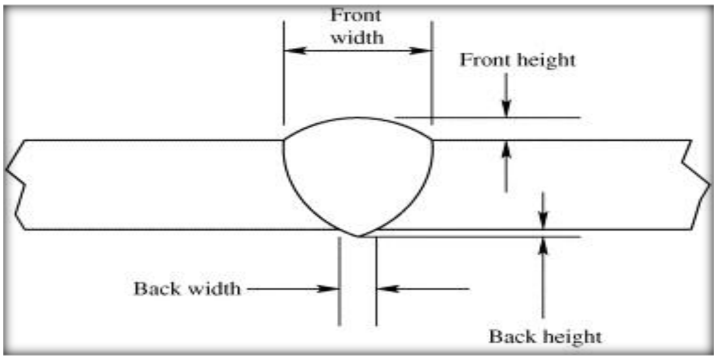

Figure 2.7: A schematic diagram showing the weld bead geometric parameters

Source: Regis Blondeau (2001)

The quality of TIG arc weld ranks higher than the quality of any of the arc welding process. High level of quality is obtain when all necessary precaution are taken. The filer's metal should be clean, the gas must be welding grade and the apparatus must be in excellent condition. When the welding current is too low, the bead is too high; there is poor penetration and the possibility of overlapping at the edge increases. When the welding speed is too fast the bead is too small and penetration is minimal. When the heat input is too great, the bead become extremely large usually wide and flat (Regis, 2001).

2.7 TENSILE MODELLING USING TIG WELDED JOINTS

The most important part of any welded specimen is to check the strength of the welding area. The most familiar test used is tensile test, impact test and also will be scan the weld part using scanning electron microscope. All of the testing process is very important in order to determine the result of the investigation. Tensile test will determine mechanical properties of the specimen such as ductility toughness and elastic modulus.

Failure is the one of the most important aspect of material behaviours because it direct influence the selection of the material or specimen for a certain application especially weld area of welding in TWB (Zuki et al. 2010).

2.7.1 Tensile Test of Tungsten Inert Gas welding (TIG)

The specimen welded TIG welding was tested to study the strength of shield metal arc welding weld area. Figure 2.8 shows the welded specimen microstructure using scanning electron microscope (SEM). The tensile properties are shown in the Table 2.4.From the table, the average data of maximum load, maximum displacement, maximum stress and the maximum strain was recorded. The average maximum load is 2.269 kN. The average max stress and % strain for the TIG weld specimen is 324.17MPa and 27.17%.

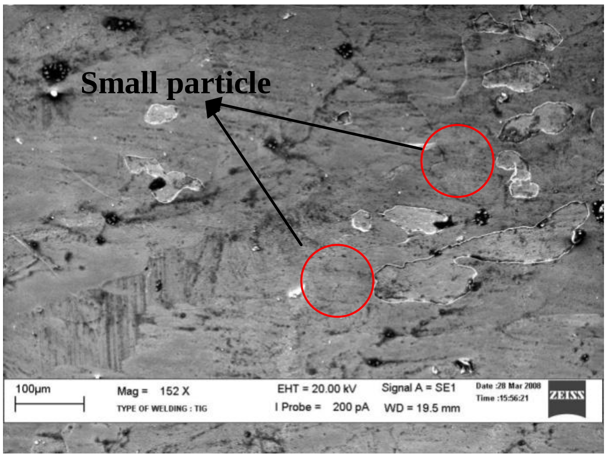

Figure 2.8: Tailor-welded TIG specimens after the tensile test with SEM picture

Source: Zuki et al. (2010)

Table 2.4: Tensile properties of the TIG specimen

Specimen	Yield Strength (MPa)	Max Stress (MPa)	% Strain	Max Load (KN)	Max Displacement (m)
1	219.08	320.57	29.71	2.244	10.74
2	220.80	322.28	26.17	2.256	10.76
3	228.68	329.65	25.63	2.307	9.733
Average	222.85	324.17	27.17	2.269	10.411

Source: Zuki et al.(2010)

2.8 INTERMETALLIC COMPOUND LAYER (IMC)

Joining of aluminium alloy using any type of welding has great difficulty since large number of brittle IMCs is formed in the joint. Although solid-state welding can be used to join the dissimilar metals by controlling the IMC layer's formation within a few micrometers, the joint's shape and size are extremely restricted by the welding equipment's